The prediction of diver visibility and its relation to spectral beam attenuation.

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LONG-TERM GOALS

The goal of the proposed research is to determine the dependence of a simple diver visibility parameter (horizontal visibility of a black disk) on the spectral beam attenuation coefficient. In particular we will investigate whether the beam attenuation coefficient at a single wavelength can be used to predict visibility or whether accurate prediction requires spectral attenuation measurements.

OBJECTIVES

- Review the existing literature on diver visibility.
- Carry out experimental determinations of the sighting range of a black disk using Davies-Colley's method together with spectral absorption and attenuation measurements in a wide range of natural optical environments.
- Determine the proper wavelength or wavelength combination for the limiting beam attenuation for the horizontal black target (minimum c wavelength, photopic c, c(532), etc.)
- Verify results using observations from the GLOW experiments and other diver visibility experiments.

APPROACH

We are reviewing the existing literature on visibility measurements in the atmosphere and ocean. Much of the work was in the gray literature and is being lost. We propose to do a review of diver visibility and put the review on our web site. We have contacted Dr. Mueller of San Diego State University who will allow us access to his complete collection of the old Visibility Lab. publications. We will also talk with Mr. R. Austin of SDSU, who is a former director of the Visibility Lab.

By using an approach similar to that of Davies-Colley (1988), we are able to obtain a large number of data points (horizontal visibility and spectral attenuation and absorption coefficients) in many different kinds of natural waters for a modest cost. In the experimental work, the disappearance from human vision of a black disk in the horizontal direction is used to determine the horizontal sighting range

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14. ABSTRACT
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At the same time we measure the beam attenuation and absorption coefficients at 9 wavelengths using an ac-9. In the Davies-Colley work the observer used an inverted periscope and the second person moved the target and measured the sight distance. Thus two people with simple tools and an ac-9 can obtain large numbers of data points in various natural waters. We will have a large dynamic range to examine the relationship between the spectral beam attenuation coefficient and visibility. By focusing on horizontal sighting range, data points can be obtained by using two small boats, alongside docks, wading in coastal waters, etc. We have examined the predictive capability of using beam attenuation coefficient measurements at a single wavelength (e.g. 532 nm) and compared that with the predictive capability of using the minimum beam attenuation coefficient.

WORK COMPLETED

- We have carried out a review of the literature in regards to the theory of the horizontal visibility of a black target.

- We have carried out numerical calculations on the influence of the ambient light spectrum on the visibility of a black target.

- We have calculated the relationship between the photopic beam attenuation coefficient, monochromatic beam attenuation coefficients, and the beam attenuation coefficient measured by broader band sources such as LEDs with a nominal central wavelength of 532 nm.

- We have shown that monochromatic or LED based measurements of beam attenuation at 532 are adequate to predict the visibility range of a black target underwater.

- We have made a large number of underwater observations in a variety of water types of the visibility of a black target together with measurements of the spectral beam attenuation and absorption coefficients.

- We have compared results of the observations with theory and have submitted an publication on this subject.

RESULTS

We have shown from the equation of radiative transfer, based on previously published results (Duntley (1963), Jerlov (1976), and Preisendorfer (1976)), that:

$$C_{vr} = \frac{N_T(r)- N_B(r)}{N_B(r)} = - \exp[-\alpha\ r], \tag{1}$$

where C_{vr} is the contrast of an object measured at a distance r from the target. $N_T(r)$ is the photopic radiance (luminance) of the target at distance r from the target, $N_B(r)$ is the photopic radiance (luminance) of the background radiance adjacent to the target observed at a distance r from the target, and α is the beam attenuation coefficient for the photopic radiance over a distance r. If the limiting contrast that a human being can detect in ample daylight (no dark adaptation) is C_L, the above can be reduced to:

$$\text{visibility range} = y = \ln(C_L) / \alpha. \quad (2)$$

The limiting contrast was given by Blackwell (1946) as 0.02. Our own observations (see below) indicate that this is closer to 0.01.

We showed that α can be defined by:

$$\exp[-\alpha r] = -\int_{400}^{700} L_B(\lambda)Y(\lambda)\,[-\exp(-c(\lambda)r)]d\lambda \left[\int_{400}^{700} L_B(\lambda)Y(\lambda)\,d\lambda\right]^{-1} \quad (3)$$

where $Y(\lambda)$ is the eye's photopic response function (see Mobley, 1994), $c(\lambda)$ is the spectral beam attenuation coefficient and $L_B(\lambda)$ is the background light spectrum adjacent to the target. The photopic beam attenuation coefficient depends on all these parameters as well as the range r. The photopic beam attenuation coefficient does not strictly obey Beer's law and is not strictly an inherent optical property.

If one assumes that the background radiance is uniform with wavelength and set its photopic luminosity equal to one (units of lumen), one can write the following equation for a uniform spectral light photopic attenuation coefficient, α_U :

$$\alpha_U = -(1/r)\ln\left\{\int_{400}^{700} Y_n(\lambda)\,[\exp(-c(\lambda)r)]d\lambda\right\} \quad (4)$$

Eq. 4, shows how to construct a photopic α_U -meter: One puts a photopic filter in front of a spectrally flat white light source and measures the attenuation. It is for this reason that Duntley, Preisendorfer, and Davies-Colley (op. cit.) used white light source transmissometers with Wratten #61 filters, which approximate $Y(\lambda)$.

We have carried out calculations to determine the influence of $c(\lambda)$ and $L_B(\lambda)$ on α. We modeled the spectra of $c(\lambda)$ and $L_B(\lambda)$,and substituted these into Eq. 3.We carried out a large number of numerical calculations with a varying yellow matter load, and for a wide depth range. Combining the results of all calculations, we conclude that:

0.96 visibility range at surface < visibility range at depth < 1.04 visibility range at surface.

The primary reason for this small effect is that the attenuation spectrum is relatively flat in the photopically important wavelength range (500 – 600 nm). The attenuation by pure water increases towards the red, whereas particulate and CDOM attenuation usually decrease towards the red. These effects are somewhat offsetting. The steepest attenuation spectrum is provided by CDOM, but its absolute value is limited by K, and its values are small in the 500 – 600 nm region. A spectrally flat beam attenuation coefficient will result in all measures of beam attenuation being the same, in which case any beam attenuation meter will correctly predict visibility. Since the product of α and the visibility range determines the limiting contrast (Eq. 2), we obtain the same inequality for α .We can thus use α_U in place of α, with an error of typically 1 to 2% and a maximum error of 4%.

In addition we modeled the effects of using commonly available beam attenuation meters as proxies for the photopic beam attenuation coefficient. Common measures of attenuation are narrow band attenuation measured with spectral attenuation meters such as the WET Labs ac-9, and red or green LED light source beam attenuation meters. We paid special attention to measurements at 532 nm, as this is the wavelength of doubled YAG lasers that are employed in a number of underwater applications. Hence a number of nominally 532 nm green LED tranmissometers are already in use. A large number of 650 nm LED source transmissometers are in use as well, so that it is useful to look at how well these can be employed to predict visibility range. We found that the visibility range as a function of particulate and dissolved beam attenuation coefficient, $c_{pg}(550)$, plus $\alpha_W(12m)$ at 550 nm (=0.081), i.e. c_{pg} (550) +0.081 was an excellent proxy for α, with errors less than 3% for a large variety of beam attenuation spectra. Modern attenuation meters are referenced to pure water, so that the water attenuation had to be added back in. As Eq. 3 showed, α of pure water (α_W) is a function of visibility range and spectral c for pure water. In order to use $c_{pg}(550)$ as a measure of α, we thus need to add α_W. We have added here α_W (12m)=0.081. Based on the model results, we also concluded that an error of less than 10% is made for visibility predictions when using $c_{pg}(532)$*0.9 +0.081 either monochromatic, or from an LED transmissometer rather than photopic α.
For 650 nm we found the relationship $c_{pg}(650)$*1.18 + 0.081 to be a good proxy for α, with errors less than 20% for the three cases of γ and two cases of $a_g(532)/c_{pg}(532)$ examined. The reason is that cpg(650)/cpg(550) is approximately equal to 1.18 (for γ=1 and $a_g(532)/c_{pg}(532)$=0.1) and $\alpha_W(12m)$ = 0.081.

Davies-Colley (1988) showed an excellent relationship between horizontal sighting range of a black 200 mm diameter disk and **Ψ**/c (blue circles, Fig. 1), where c was measured with a white light source transmissometer equipped with a nearly photopic response filter. **Ψ** was found to be a weak function of c and averaged 4.8. Since this is the existing hypothesis, we have tested our data against it.

Our own data was taken with a WET Labs ac-9 spectral attenuation meter at 532 nm (red circles in Fig. 1) and a 200mm black disk obtained from Davies-Colley, that matched the disk used for his observations. The disk is suspended in the water about 20 cm below the surface. The observer uses an inverted periscope to view the target at the depth of the target. The viewer moves away from the target until the edge of the target is no longer discernable relative to the background. The light field must be plane parallel. It is important to have no objects behind the target for at least three optical depths. In addition reflecting objects near the sight path, such as white ship's hulls, introduce errors by generating non-uniform light fields. These data contain a wide variety of locations, such as coastal ocean, estuaries, rivers, and lakes. Similarly, a wide range of illuminations (direct sun, 100% overcast, etc.) are included. The visibility of the disk was obtained from a dock or a boat using an inverted periscope, so that the viewer is looking at the same depth as the target.

We see from Fig. 1 that our data nearly agrees with Davies-Colley's conclusion that visibility range = 4.8/α. More precisely, Davies-Colley's best fit is given by the green line in Fig. 1, which also matched our data to within five percent. Our data tends to fall slightly below the 4.8 line. We found an average value of 4.55 for the product of α and visibility range. The central red line on figure 4 shows this 4.55/α relationship, and the upper and lower red lines are the +/- 20% lines. The difference is about 5% which is well within the experimental errors of the measurements.

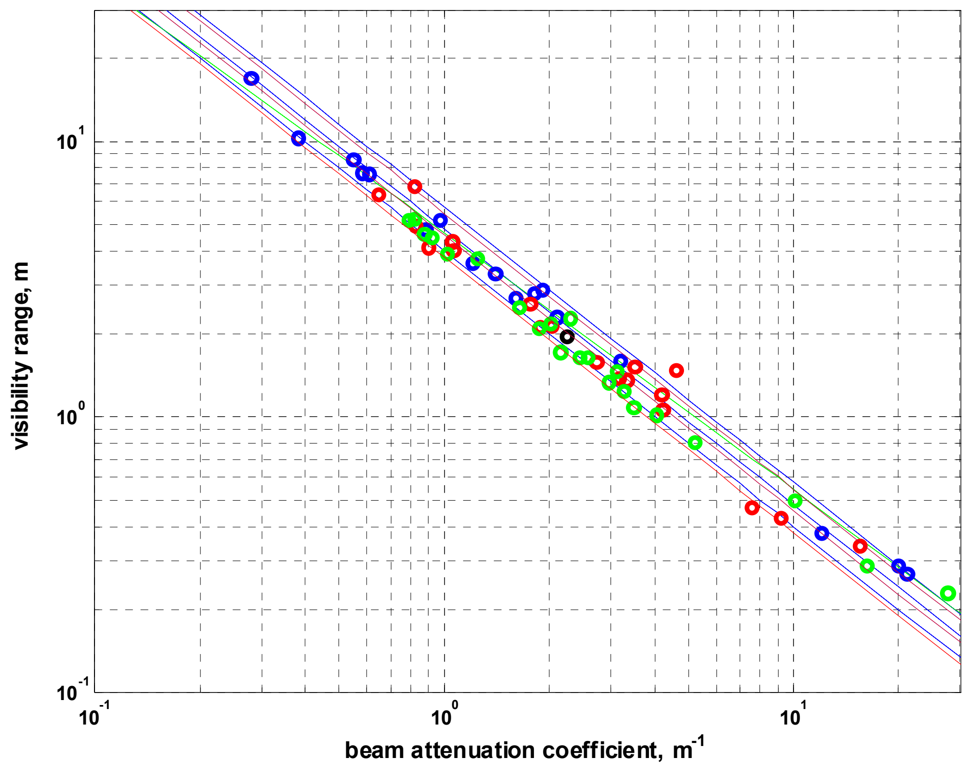

Figure 1.[Graph:Horizontal visibility of a 200 mm diameter black target is shown to have an excellent inverse correlation with photopic beam attenuation as obtained from proxy measurements at 550 and 532 nm. Blue points, Davies-Colley, "green" c-meter; red points, Zaneveld, c(532)*0.9+0.081; black point, Twardowski c(532)*0.9+0.081; green points, Pegau,c(532)*0.9+0.081; blue lines visibility range = y = 4.8/α and +/- 20% lines; green line visibility range= y=(5.207- 0.368 lny)/α ; red lines visibility range = y = 4.55/α and +/- 20% lines; r^2 = 0.985.]

For 650 nm we found that c(650)*1.18 +0.081 was an adequate proxy for the photopic beam attenuation coefficient. We obtained a correlation coefficient of r^2 = 0.959 for the experimental correlation of the modified 650 nm measurement with visibility range.

We have thus shown that a robust underwater visibility parameter exists, that can readily be measured with existing proxy instrumentation. This visibility parameter is the visibility of a black disk in the horizontal direction. Many other targets and geometries exist. These all require more parameters to predict and so are not as useful in tactical situations. An experienced diver can learn to extrapolate the simple parameter described here to other visibility situations.

IMPACT/APPLICATIONS

Special Operations and Mine Warfare require the prediction of visibility for divers and cameras using ambient (natural) light. Theoretical models show that contrast reduction in the horizontal direction and hence the simplest description of diver visibility depends directly on the photopic beam attenuation

coefficient. This parameter can be measured using transmissometers, preferably at 532 nm, but with a reduction in accuracy, 650 nm is adequate, it can be modeled using combined physical, biogeochemical, and optical models, or it can be estimated from ocean color imagery. The beam attenuation coefficient of interest is the attenuation of the natural light spectrum convolved with the spectral responsivity of the human eye (photopic response function).

TRANSITIONS

Beam transmissometers were used in the recent Iraq war to predict diver visibility. The above equations should improve the accuracy of the predictions and put them on a firm theoretical footing. In addition we have shown how measurements using transmissometers with different light sources can be combined to obtain the same visibility parameter.

RELATED PROJECTS

Development of a Scattering-Attenuation Meter (SAM). P.I. Dr. M. Twardowski, WET Labs.

The goal of this project is to develop and characterize a compact dual wavelength optical beam attenuation meter, the SAM. The SAM is designed to meet the needs of applications demanding beam attenuation measurements from a sensor that is hydrodynamic, small, robust, and low maintenance. Many compact, cost-effective observation platforms now gaining widespread use by the Navy and the ocean research community require sensors with these qualities, including Automated Underwater Vehicles (AUVs) such as the REMUS, Unmanned Underwater Vehicles (UUVs), profiling/gliding floats, ship- and air-launched expendable devices, towed vehicles, and ship-board sensing systems. The device has a flat sensing face exposed to the water. The flat surface allows for flush mounting on an AUV, underwater hull, or in any application requiring a hydrodynamic surface. The SAM components are potted in a monolithic body with encapsulated optics and electronics. An example of data obtained with this device is shown in Fig. 2 below.

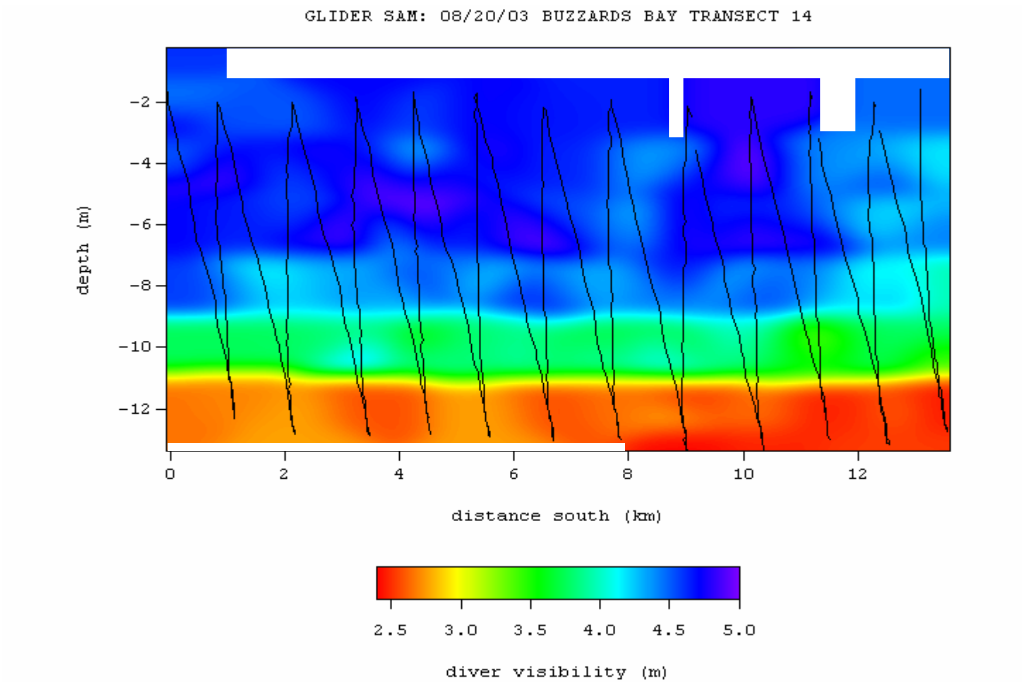

Figure 2.[A transect of visibility range obtained using a Scattering Attenuation Meter and the formulae in this report in Buzzards Bay, Mass. The black line is the track of the profiling instrument through the water column. The visibility range has values of larger than 5m near the surface and less than 3m at 12m depth just above the bottom. Figure courtesy Dr. M. Twardowski, WET Labs.]

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PUBLICATIONS (from this grant only)

Zaneveld, J. R. V. and W. S. Pegau, " A robust underwater visibility parameter" submitted to Optics Express.